Charge Behavior in Palm Fatty Acid Ester Oil (PFAE) / Pressboard Insulation System under Flow Condition in Power Transformers

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Abstract- **From viewpoints of low environment impact, Palm Fatty Acid Ester oil (PFAE) is potent insulating liquid for power transformers because of its high biodegradation performance. Moreover, PFAE has high permittivity, low viscosity, high thermal and chemical stability and high productivity. These characteristics well satisfy the requirement of electric insulation performance in power transformers. In this paper, electric field distribution in a PFAE / pressboard insulation system was measured with a Kerr electro-optic technique at various oil flow conditions under dc voltages and the charge behavior was investigated systematically. We discussed the difference of the flow electrification characteristics between PFAE and mineral oil, and its mechanism was discussed based on the charge behavior in oils.**

I. Introduction

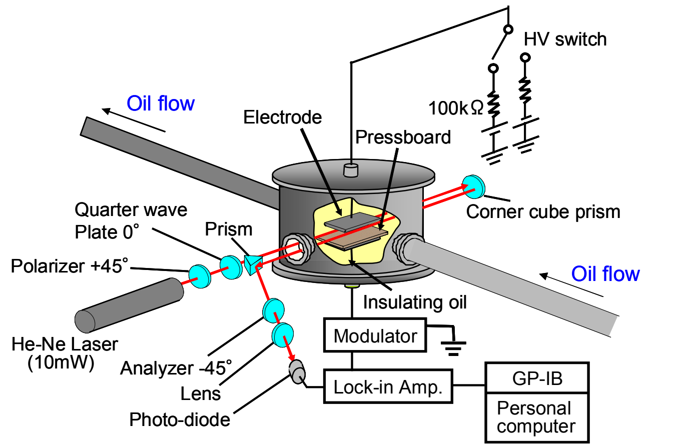
Mineral oil has been used for a long time as an insulating oil for large power transformers. Recently, on the issues of depletion of resources and environmental damage at leakage, demand on environment-friendly insulating oil is increasing. Various vegetable oils have been investigated[1-3], especially, PFAE[4] has advantages of productivity, good biodegradability, excellent insulating performance, high cooling ability and good oxidation stability. PFAE is expected as a potent substitute for mineral oil. For application of PFAE to power transformers, the flow electrification characteristics in an oil / pressboard (PB) composite insulation systems must be clarified, as well as insulation characteristics of PFAE. The flow electrification is easy to occur when the insulating oil flows on PB[5], and electric charges tend to be accumulated on PB. As the charges generates the electric field distortion, charge behavior in PFAE should be clarified for the rational insulation deign and the enhancement of insulating reliability of power transformers.

In this paper, the electric field strength in PFAE was measured using the Kerr effect under dc voltages in various PFAE conditions (PFAE at rest (without flow) / uncharged PFAE with flow / charged PFAE with flow), and was compared with that in mineral oil. The difference of temporal charge of the electric field strength between two oils was clarified. And it was discussed based on the charge behavior.

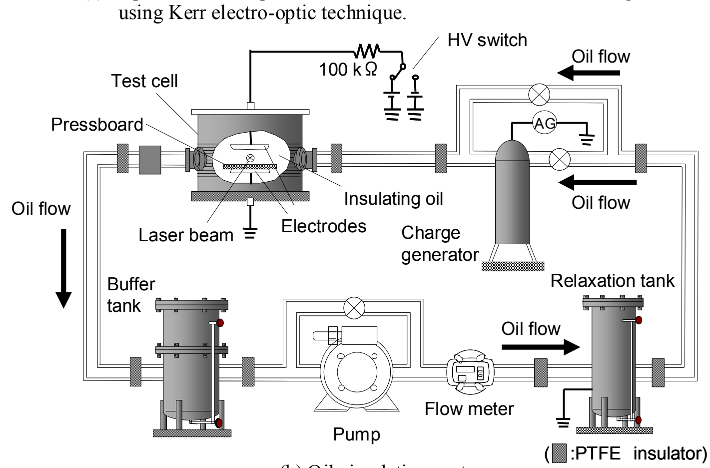
II. Experimental Setup

Figure 1 shows an experimental setup. The setup consisted of a test cell, oil pump, charge generations and two tanks, i.e. a relaxation tank and buffer tank. It was filled with insulating oil (PFAE or mineral oil). The insulating oil was forced to flow by the pump at rate of 4 ~ 14 ℓ/min. Electric charges were generated in the charge generator by using an oil filter. As the filter absorbed negative charges, the oil was changed with positive polarity. The leakage current from the charge generator was measured by the high resistance ampere meter A_G. When the charge generator was bypassed, the uncharged oil can flow. Electric field strength in oil was measured at the test cell by using the Kerr electro-optic technique[6, 7]. The sensitivity of the measurement was 0.05 kV/mm.

Oil properties are listed in Table 1. Figure 2 shows the electrode configuration placed in the test cell. 1mm thick PB was placed on the grounded electrode of the parallel-plane electrodes.



(a) Experimental setup for electric field measurement in insulating oil using Kerr electro-optic technique.



(b) Oil circulation system

Fig.1. Experimental setup for changing measurement under oil flow condition.

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Table 1. Properties of insulating oil.

	PFAE	Mineral oil
Specific gravity [g/cm^3] at 15℃	0.86	0.87
Kinematic viscosity [mm^2/s] at 40℃	5.06	8.36
Relative permittivity at 80℃	2.9	2.2
Volume resistivity [Ω·cm] at 80℃	7.1×10^{12}	4.6×10^{14}
tanδ at 80℃	0.31	0.001
Flash point [℃]	176	145

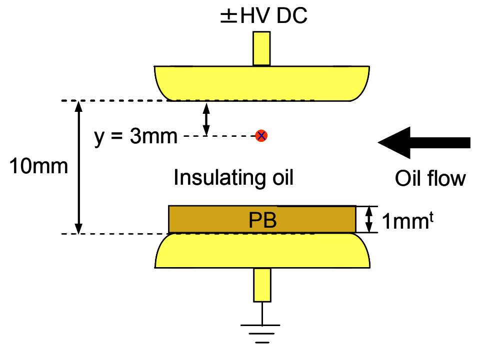


Fig.2. Electrode configuration.

The upper electrode was connected to a high voltage switch, and the polarity of the applied voltage could be reversed. Electric field was measured at y=3 mm from the upper electrode. All experiments were carried out at room temperature.

III. Experimental Results And Discussions

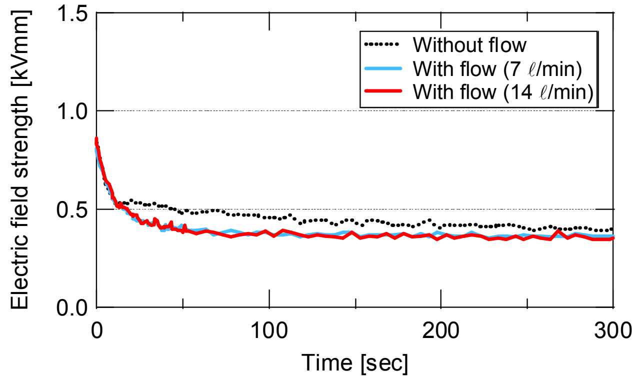
A. *Uncharged Oil Flow*

Figure 3 shows the time dependence of electric field strength in both PFAE and mineral oil (deteriorated insulating oil with the volume resistivity of 10^{12} Ω·cm at 25℃) at dc voltage of +10 kV. Electric field strength generated at moment of voltage application and decreased with time in both mineral oil and PFAE. The decrease of the electric filed strength was observed in oils with and without flow. This phenomenon can be explained with the charge behavior. The oil has no net charge, but there are positive and negative charges in oil. The positive charges in oil drifted due to the applied electric field and accumulated on PB. On the other hand, negative charges drifted and disappeared at the anode electrode. As a result, electric field in oil gap was weakened by the accumulated positive charges on PB.

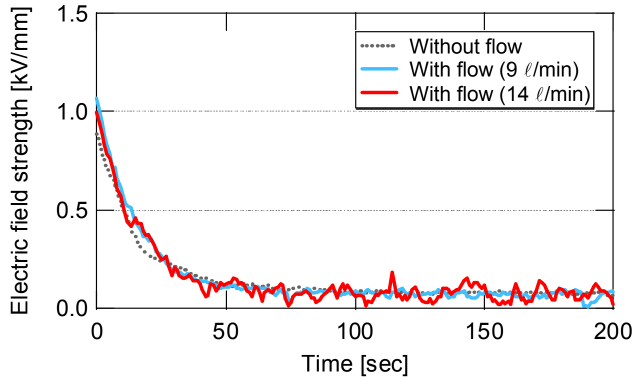
Next, we focused on the difference of the electric field strength between oils with and without flow. In mineral oil, the electric field strength decreased faster in flowing oil than in oil without flow, as shown in Fig. 3(a). On the other hand, in PFAE, electric field strength decreased monotonously with time in oils with and without flow and no difference was observed as shown in Fig. 3(b).

The difference of the temporal change between PFAE and mineral oil can be explained with the surface charge density on PB. Firstly, the charge behavior in mineral oil was discussed in oils with and without flow.

Surface charge density q on PB followed the continuity equation (1) of dielectric flux density. By substituting the measured electric field strength in eq. (1), q can be derived. The calculated value of q is shown in Fig. 4. The value of q



(a) Mineral oil



(b) PFAE

Fig.3. Time dependence of electric field strength at y=3mm in between oil at rest without flow and uncharged oil with flow.

$$\varepsilon_{oil}\, E_{oil} + q = \varepsilon_{PB}\, E_{PB} \qquad (1)$$

ε_{oil}, ε_{PB} : Relative permittivity of oil and PB
E_{oil}, E_{PB} : Electric field in oil and PB
q : Surface charge density on PB

changed with time. The change can be classified into three time regions. The charge behavior in each time region is illustrated schematically in Fig. 5.

<At region I> Initial ions generated in oil move toward the PB surface and accumulate there. In this region, the initial ion density dominates the time transition of electric field.

<At region II> At the end of region I (time t_1), almost all initial ions are swept and very limited number of ions exists in oil gap in oil without flow. The value of surface charge density on PB at the end of region I was estimated to be 200 pC/mm^2. This value corresponded to the charge density of 22 pC/mm^3 in oil. On the other hand, in flowing oil, because oil always carried charges into the oil gap, the ion density in the oil gap continues the constant value of 22 pC/mm^3. After time t_1, very limited number of charges drifted from the vicinity of the electrode, and the speed of the charge accumulation slowed down. Therefore, the charge accumulated continued, and the density became larger than in oil without oil.

<At region III> The surface charge density on PB saturated and the value is determined by the volume resistivity of oil and PB. So, the saturated surface charge density is determined uniquely, and is

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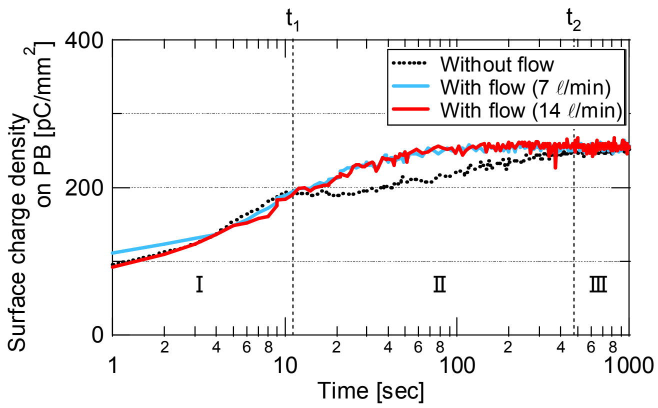


Fig.4. Time dependence of charge density on PB in mineral oil.

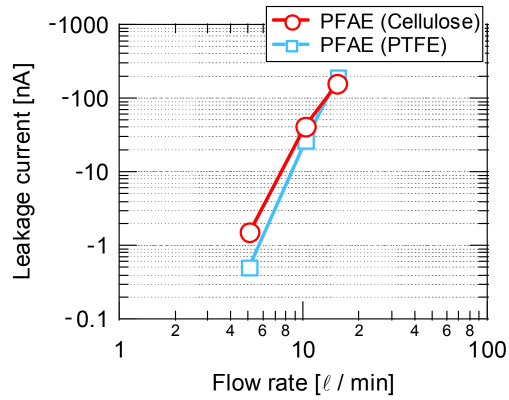


Fig.6. Relationship between flow rate and leakage current.

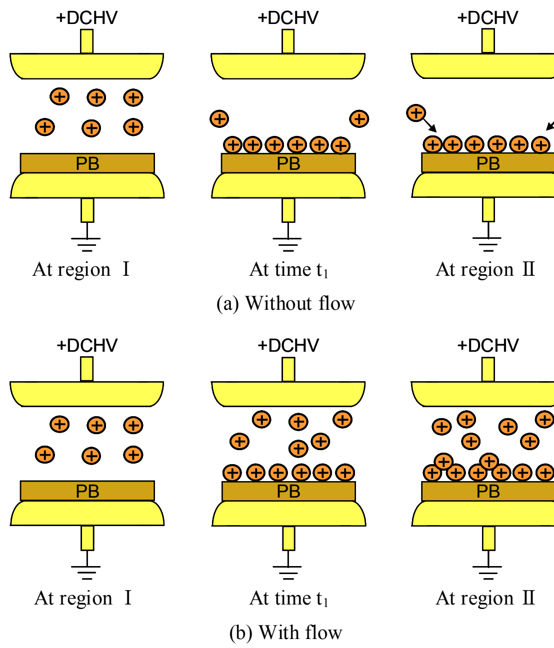


Fig.5. Schematic illustration of charging mechanism with and without flow in mineral oil

independent of the flow condition. The saturated surface charge density was 260 pC/mm^2, which was different from the value at time t_1 by 60 pC/mm^2. Charges of 60 pC/mm^2 were carried from the outside of the electrode by flowing oil.

As mentioned above, characteristics in three mineral oil conditions in Fig. 3(a) could be explained based on the difference of the change accumulation mechanism between oils with and without flow.

Secondly, the charge behavior in PFAE was discussed. Electric field strength decreased monotonously as shown in Fig. 3(b), and region II did not appear. This means that the temporal change of the surface charge density in oil without flow was almost equal to that in flowing oil. These characteristics of PFAE differed from those of mineral oil. As the resistivity was about two orders lower in PFAE than in mineral oil, large quantities of charges were likely to exist in PFAE. The amount of charges in PFAE was sufficient to accumulate rapidly on the PB surface to the saturation level. Therefore, the temporal change of electric field strength was the same trend between oils with and without flow.

B. *Charged Oil Flow*

(i) Leakage current measurements

The leakage current from the charge generator was measured changing the flow rate from 4 to 14 ℓ/min. Figure 6 shows relationship between the leakage current and flow rate in PFAE. Leakage current increased when flow rate increased, and less depended on the kind of filters. The charge density in oil was evaluated from the leakage current, and its value was about 0.8 pC/mm^3 at 14 ℓ/min. This value was nearly equal to that in fresh mineral oil at 14 ℓ/min. According to the measured results, the cellulose filter was used in the following experiment.

(ii) Electric field measurements

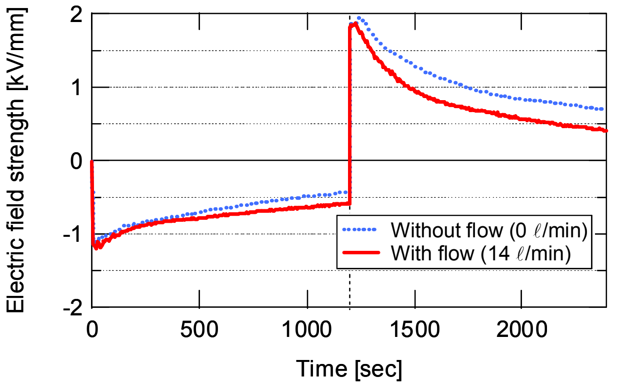
Figure 7 shows the time dependence of electric field strength in oil gap when the polarity of the applied voltage was reversed from -10 kV to +10 kV in both PFAE and fresh mineral oil. The electrode configuration in Fig. 2 was used in the measurements. Examined flow rates were 0 ℓ/min and 14 ℓ/min.

In mineral oil (Fig. 7(a)), dc voltage of -10 kV was applied to the upper electrode at t = 0 sec, and the voltage was reversed from -10 kV to +10 kV at 1200 sec. Electric field strength at the instant of the polarity reversal was about twice that at t = 0 sec, irrespective of the flow rate.

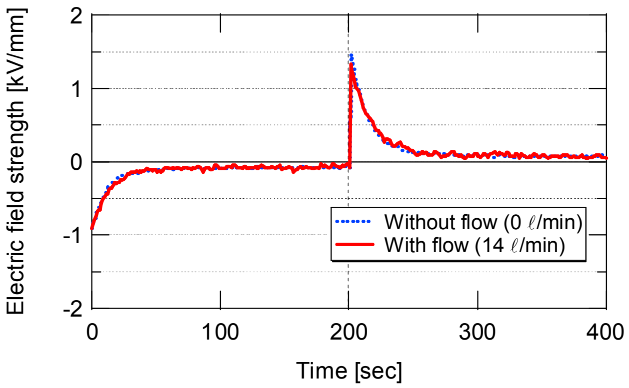
Electric field strength decreased faster in oil at rest than in flowing oil before polarity reversal. However, after polarity reversal, electric filed strength decreased more slowly in oil at rest than in flowing oil.

In PFAE (Fig. 7 (b)), the voltage polarity was reversed from negative to positive at t = 200 sec. Electric field strength at polarity reversal was 1.5 kV/mm, which was 3/4 times lower than the theoretical value. This was caused by the fact that the decay of electric field strength in PFAE was very fast and exceeded the response time of the measurement systems. Electric field strength decreased with time both in oil with and without flow. The temporal change in oil at rest was almost similar to that in flowing oil. This phenomenon was quite different from that in mineral oil. Their difference can be explained by the mechanism of charge supply shown in Fig. 8.

<Before the polarity reversal> In Fig. 8(a), most positive charges carried by oil flow were drifted to the upper electrode and disappeared there. But the rest stayed in the oil gap and neutralized partially the negative charges accumulated on the

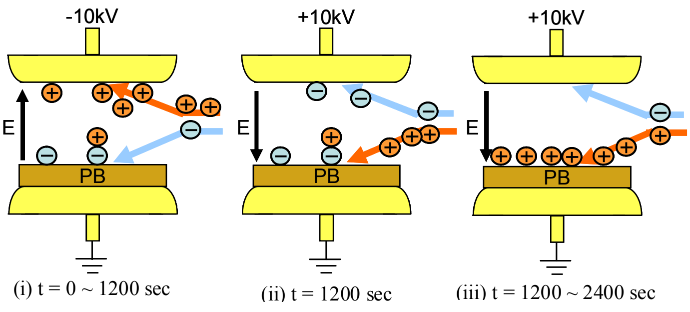


(a) Mineral oil

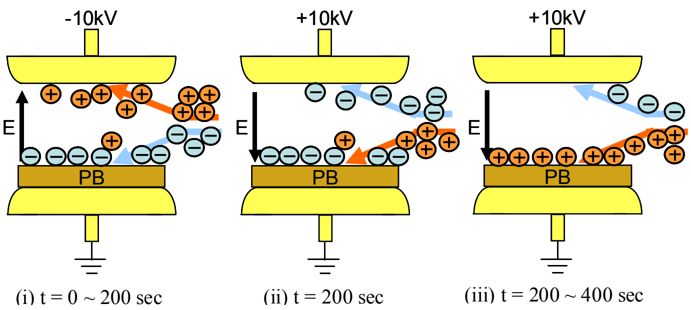


(b) PFAE

Fig.7. Time dependence of electric field strength at y=3mm in oil at rest without flow and charged oil with flow.



(a) Mineral oil



(b) PFAE

Fig.8. Schematic illustration of charging mechanism in charged oil with flow.

PB surface. So, electric field strength in flowing oil decreased more slowly than that in oil at rest.

<At the instant of the polarity reversal> The applied field superimposed on the electric field generated by the accumulated negative charges. Electric field strength at the instant of the polarity reversal was about twice of that at t=0 sec.

<After the polarity reversal> In Fig. 8(a), positive charges were supplied continuously by flowing oil and accumulated on the PB surface. So, electric field strength decreased faster in flowing oil than that in oil at rest.

The charge behavior in flowing PFAE is basically the same as that in mineral oil. The ion density in PFAE is much higher than that in mineral oil, and the amount of positive charges generated by flow electrification was much smaller than the amount of charges which PFAE had originally. Owing to these causes, the influence of flowing oil on the change accumulation on the PB surface (i.e. temporal change of electric field strength in Fig. 7 (b)) was not clearly observed.

IV. Conclusions

Electric field strength in a PFAE / PB composite insulation system was measured with the Kerr electro-optic technique under various conditions of flowing oil. Obtained data were compared with those in mineral oil and were discussed based on the charge behavior. Following results were obtained.

(1) Leakage current in PFAE increased when oil flow rate increased, and the charge density in oil was evaluated from leakage current and its value was about 0.8 pC/mm^3 at 14 ℓ/min.
(2) Electric field strength in a PFAE gap decreased with time. Its decrease characteristics were not influenced by charged PFAE flow. However, in mineral oil, the influence of charged oil flow was obvious.
(3) These different characteristics were caused by the difference of the ion density between two oils, because the ion density of PFAE is much higher than that in mineral oil.

References

[1] T. Blacburn, K. Budin, B. Finlay, S. Islam and L. Mcpherson, “Australian Experience with the Development, Ageing and Maintenance of Vegetable-Based Insulating Oils,” CIGRE 2006, D1-301, 2006.

[2] T. V. Oommen, “Vegetable Oils for Liquid-Filled Transformers,” IEEE Electric Insulation Magazine, Vol. 18, No. 1, 2002.

[3] K. Nakamura, K. Kato, H. Koide, K. Fuji and H. Okubo, “Kerr Electro-Optic Measurement of Electric Field Distribution in Rapeseed Ester Oil and Pressboard Composite system,” ICDL 2005, pp. 405-408, 2005.

[4] T. Hikosaka, A. Yamazaki, Y. Hatta, H. Koide, T. Kanoh, H. Iwabuchi, Y. Hoshida and J. Yamada, “Basic Characteristics of Environment-Conscious Transformer Impregnated with Oil Palm Fatty Acid Ester (PFAE),” 2007ISH, T8-13, 2007.

[5] M. A. Brubaker and J. K. Nelson, “Development and Calibration of a Streaming Electrification Model for a Cellulose Duct,” IEEE Trans. on Dielectrics and Electrical Insulation, Vol. 4, No. 2, pp. 157-166, 1997.

[6] M. Wakamatsu, K. Kato, H. Koide, K. Fuji and H. Okubo, “Behavior in Flowing Charged Oil / Pressboard Composite Insulation System Based on Electric Field Measurement,” CEIDP 2003, pp. 189-192, 2003.

[7] K. Kato, Y. Hashiba, Y. Nakagami, M. Miyamoto and H. Okubo, “Study on Charge Behavior in Flowing Transformer Oil / Pressboard Composite Insulation System Using Electro-Optic Field Measurement,” ICDL 1999, pp. 349-352, 1999.